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Models for Fire-Driven Heat and Moisture Transport in Soils

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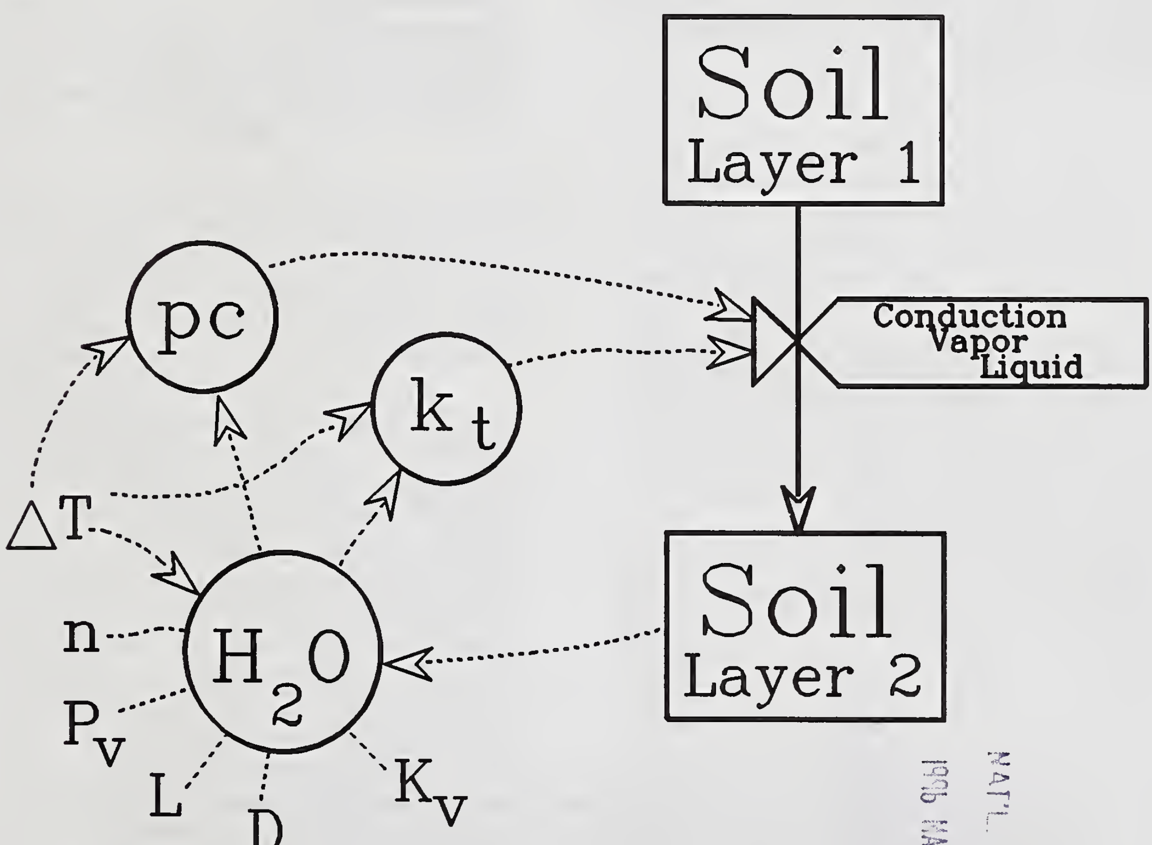

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Introduction

Transfer of heat into the soil beneath a wildland fire causes a large number of onsite fire effects (Hungerford 1990) that include mortality of or injury to subsurface parts of surface plants or whole organisms that live within the soil, thermolysis of organic matter, oxidation or volatilization of free mineral components, and other physicochemical changes that can be as extreme as fusion of mineral soil constituents. To predict the nature and extent of such effects it is necessary to know the temperature history as a function of depth within the soil beneath the fire.

To predict the temperature history profile in a soil under a fire, we need to know the history of heat input to the soil surface or the surface temperature history and to model the response of the soil to this stimulus. In this paper we focus on the challenge of modeling the response of the soil to boundary heating or temperature history.

Modeling the soil's thermal response would be relatively simple if not for moisture and its movement because of spatially nonuniform heating (Morse and Feshbach 1953; Steward and others 1990). The very large heat of vaporization of water and the ease with which water vapor can move through a porous soil matrix cause the transport of heat to be dominated by water vapor movement for temperatures near the boiling point of water (Aston and Gill 1976; Cheng 1978; Eckert and Faghri 1980; Luikov 1975). The relative immobility of water as a liquid in soil, and the high value of liquid water's thermal conductivity relative to that of air in the soil pores, make the thermal conductivity of the bulk soil medium sensitive to its liquid water content when liquid water occupies a significant volume fraction within the medium (Campbell 1985; deVries 1958; Jury 1973; Peter 1992; Philip and deVries 1957).

All this complicates the accurate modeling of heat transport within soils by making it necessary simultaneously to model the movement and concentration of water in liquid and vapor phases as well as the transport of heat by thermal conduction. Furthermore, a complete model must include variations with moisture content and temperature of the parameters that control the transport of heat, liquid water, and water vapor. The dependence of rate-controlling parameters (such as thermal conductivity, vapor diffusivity, and hydraulic conductivity) upon the dependent variables means that the equations are mathematically nonlinear. This nonlinearity, makes it not valid to solve a series of simple problems and construct more complex cases by linear superposition of the "simple" solutions. Nonlinear systems of equations do not generally admit to analytical solutions. Thus, we need to resort to numerical integration of the model's partial differential equations, introducing a whole new realm of potential pitfalls. Despite these complexities, a fairly rich literature on the topic exists.

Heat transport and moisture movement within soils have been studied in soil science and microclimatology (Al Nakshabandi and Kohnke 1965; Bhuiyan and others 1971; Campbell 1985; deVries 1958; deVries and Afgan 1975; Philip and deVries 1957). There is a wealth of theoretical and empirical knowledge about this phenomenology and the modeling of it. But the models and relationships are frequently restricted to the temperature regimes, heating rates, and spatial gradients of temperature and moisture that occur naturally in diurnal cycles of heating and cooling (and wetting and drying) and as a result of precipitation, drought, and irrigation.

Only recently (Hungerford 1990) have investigations been extended to the temperatures, heating rates, dryness states, and gradient magnitudes that characterize the fire environment (Aston and Gill 1976; Campbell and others 1992, 1993, 1994, 1995; Jury 1973; Peter 1992; Schroeder 1974; Steward and others 1990). However, none of these authors have drawn heavily upon parallel literature from the disciplines of engineering and geophysics.

In those research communities, analytical, numerical, and experimental investigations of coupled heat and mass transport in porous media have been carried out for more than a century (Catton 1992; Kaviany 1991; Rust and Roberts 1990; Tang and Bau 1992). Engineers view this as a special case in the general field of heat transfer (Bejan 1984). Half of this recent volume (Kaviany 1991) is devoted to analysis of heat and mass transport in the instance that the interstitial fluid exists in two phases, which is the case of interest in fire-heated soils.

This paper documents a research joint venture. The objectives:

1. Survey the literature across several disciplines that address heat and mass transport in porous media, assessing any differences in approach to modeling these processes among the different disciplines.
2. Document test exercises of two models that are potentially useful for assessing effects of wildfires.
3. Identify opportunities for advancing the state of the art in modeling fire-driven transport of heat and moisture in soils.

Survey of Literature

A literature survey was undertaken through the technical libraries at Montana State University and at Intermountain Fire Sciences Laboratory, as well as the authors' personal literature collections and preprints from technical meetings. We found descriptions of computer simulation models for heat and mass transport in porous media in the literature of soil science and its derivative subdisciplines, and in publications by engineers and by geophysicists.

Models with Soil Science Ancestry

Hungerford (1990) offers a definitive statement of the motivation for modeling heat and moisture transport in soils for the purpose of predicting the effects of wildland fires and provides a comprehensive survey of empirical and interpretive field studies of the effects of fires in forest and rangeland settings. He provides an exhaustive list of the mathematical models that had been put forward by mid-1990 for the prediction of heat and moisture transport in soils heated by fires.

The pioneering works by J. R. Philip and D. A. deVries (deVries 1958; deVries 1975; Philip 1975; Philip and deVries 1957) explored and analyzed the movement of moisture and the transfer of heat in soils by starting at the size scale of the soil particles. They sought to connect soil descriptive parameters such as the relative abundances of mineral types in the soil, particle shapes and size distributions, bulk density, soil environmental parameters such as temperature and liquid moisture volume fraction, and the constitutive parameters describing macroscale phenomenology; such as hydraulic conductivity, effective vapor diffusivity, and apparent thermal conductivity. This approach has had considerable success and is the current paradigm of the soil science community for modeling heat and moisture movement in response to diurnal fluctuations of the forces driving them.

deVries Formulation—In a survey paper, deVries (1958) summarized and generalized simultaneous differential equations for the transfer of heat and of moisture presented the year before (Philip and deVries 1957) but is available in restricted-circulation publications and in a fragmented form.

We found no derivations of the moisture and heat transport equations in either of these citations. The conservation of mass laws for water vapor and for liquid water are used with models for fluxes embedded when they are stated, and an energy conservation equation is assembled around the Fourier transient heat conduction equation. The later paper is summarized briefly here, emphasizing a few confusing or inconsistent aspects of this important work.

Phenomenological equations relate moisture fluxes in liquid and vapor phases to gradients in temperature and moisture content. These relationships would supposedly arise from the separation of the equation expressing conservation of momentum for the medium considered as a continuum and then decomposed into its parts: soil particles, liquid water, water vapor, and interstitial air. This would be the paradigm in an engineering approach.

Two critical assumptions appear early in the paper:

1. The moist soil medium is microscopically isothermal (all components in the near neighborhood of a location are assigned the same temperature) yet large temperature gradients can exist across pore spaces between solid particles. deVries does not discuss the contradiction in this two-part assumption.
2. Water vapor and liquid water are in local vapor pressure equilibrium. This assumption allows the combining of liquid water content and water vapor content to express a water content distribution unambiguously, in absence of hysteresis, as the apportioning between vapor and liquid, then depends uniquely upon porosity and local temperature.

While neither vapor buoyancy nor liquid viscosity are found explicitly in the parameters given, the binary molecular diffusion coefficient of water vapor in air appears in proportionality constants for both thermally induced movement of vapor and movement of vapor in response to gradients in water potential. The rate of evaporation, expressed as rate of change

of mass of water (measured as equivalent volume of liquid water) per unit volume per unit time, appears as a source term in the primitive form of the vapor motion equation and as a sink term in the liquid motion equation. Instead of relating the rate of evaporation to the net absorption rate of energy, after accounting for sensible heat accumulation, the term is eliminated by summing the equation for water vapor conservation and the equation for liquid water conservation to form an equation for global conservation of water. This step illuminates a difference between the soil science approach and that of the investigator of the effects of fire.

The flux of heat is related to the transport of sensible and latent heat by water vapor, transport of sensible heat by liquid water movement, and heat conduction through the continuum. At first, conduction through the continuum is modeled by a "hypothetical" thermal conductivity, λ^*, understood to characterize soil in which the moisture distribution is fixed (deVries 1958, eq. 10). Later, this symbol is replaced by the collection:

$$\lambda - L\, \rho_l\, D_{Tv}$$

where λ is identified as the "apparent conductivity of the medium including the effect of vapor distillation due to temperature gradient," L is the latent heat of vaporization of water, ρ_l the density of liquid water, and D_{Tv} the thermal diffusivity of water vapor within the soil medium. The reader is cautioned that the two quantities are not equal because the heat fluxes in different parts of the medium are not additive.

An investigation of steady state heat conduction concludes the paper and illustrates the model's nonlinear character. A plot of isothermal moisture conductivity (velocity of liquid water movement per unit gradient of water potential, with potential expressed as hydraulic head) and isothermal moisture diffusivities (as vapor and liquid) in relation to gradients in moisture content show strong sensitivity to water content. Another plot similarly shows isothermal liquid water potential as a function of liquid moisture content and moisture diffusivities in response to thermal gradients as strongly dependent upon liquid moisture content.

Using the mathematical relationships illustrated in these two figures, deVries, found steady state equations for temperature gradient and liquid moisture gradient by setting to zero the time dependent terms (local temperature rise rate and moisture accumulation rate) and the moisture flux. He then solves these steady state equations for the steady state spatial temperature and moisture gradients as a function of liquid moisture content. The final two figures in the paper display the results of these manipulations for a light clay and for a medium sand soil, at 20 °C with a constant horizontal heat flux of 10^{-3} cal/s cm^2 (about 42 W/m^2). The moisture and temperature distributions in space are not given but can be inferred qualitatively from these graphs to be approximately as follows: For the light clay soil, volumetric moisture content rises exponentially with distance from the plane of heat application, with a characteristic length of about 10 cm. When the liquid moisture content reaches about 0.05, the slope of this curve increases by a factor of about 15; the moisture content rises abruptly and rounds off to its asymptotic value of about 0.12. The physical processes that enforce such a variation of moisture content with distance are not extensively discussed. For a medium sand, the moisture content varies initially with distance from the plane of heat application again as an exponential, but with a characteristic length nearer 1 mm. Upon reaching a liquid moisture content of about 0.005, the curve flattens abruptly, the distance scale of the exponential growing to about 80 cm. This profile would resemble a slightly round-shouldered step function.

The parameter values used by deVries are representative of the concerns of soil scientists in quantifying phenomenology associated with irrigating, the drying of soils heated by sunshine, and evaporation of soil moisture into a dry atmosphere. The heating rates and temperature levels of interest in soils under fires are, of course, substantially different. Some of the features of the model presented by deVries are confusing or surprising probably due to the differences in technical backgrounds and in motivation for addressing this complex phenomenology. Had an engineer specializing in fluid mechanics or in heat transfer described the processes, the terms used and the emphasis would be much different. An engineer would have selected different ranges of parameters, if the perturbation of soil temperature and moisture profiles were to be inferred due to heating by a fire in the surface mantle.

Most modern engineering audiences would find the deVries (1958) formulation deficient in at least two respects: First, the model contains no equation for the conservation of momentum. Because there is no explicit expression of a force balance, one is left to ponder: Does the water vapor go up or down when the soil is heated on the upper surface? The vapor tends to move from high temperature toward low temperature, but also to move from high toward low moisture concentration. The mechanical forces are not identified except in limiting forms, nor does the acceleration of gravity appear in the model. Thus, the phenomenon that nonuniform pressure accelerates a fluid toward lower pressure is omitted, so water vapor has no buoyancy or tendency to rise. Conditions under which the neglect of buoyancy is valid need to be established.

Second, the energy conservation equation is not derived from the energy transport equation of continuum mechanics, so the transfer of energy by mass movement is "added on" to the Fourier heat conduction equation. Such a derivation taxes comprehension because the heat conduction equation employs an apparent thermal conductivity that includes the transport of heat by vapor movement. This contribution is then subtracted from conductivity measurement data so the effect can be added in to the vapor movement model. This formulation does not readily permit differences in temperature between liquid, vapor, and mineral constituents, which would be relatively simple to accommodate in a model derived from the perspective of continuum mechanics.

Although these aspects of deVries' (1958) formulation are not discussed in later literature, this watershed work gave us a model for the coupled transport processes that has persisted largely unchanged, explanatory power must be acknowledged despite any uncertainties raised here.

Fire Heating Model of Aston and Gill—Another early and important model is that of Aston and Gill (1976), who addressed the problem for conditions of heating by a surface fire. These authors address the modeling of heat and moisture transport in soils in the vertical direction only, but generalization of their equations should be straightforward.

Compared to deVries' complicated formulation, that of Aston and Gill embodies simplicity even though it rests upon three coupled diffusion equations, each with a source term. Equations are posited as phenomenological descriptions of sensible heat transport, liquid water transport, and water vapor transport. Not emphasized is the assumption that all components share a local temperature.

The transport of sensible heat is modeled without mass transport except that the rate of condensation of water vapor, multiplied by the latent heat of vaporization, appears as a source term in the transient Fourier equation for heat conduction. In this equation, the specific heat capacity per unit volume is a function of the porosity and liquid water content of the soil, and the conductivity of the medium as a continuum is related empirically to the same parameters, following Al Nakshabandi and Kohnke (1965). Transport of sensible heat by moisture (as liquid or vapor or both) is incorporated through use of an empirical thermal conductivity (deVries' "apparent" thermal conductivity), for which measurements usually exist only at low temperatures. The authors used a linear function of temperature as an empirical correction factor of the thermal conductivity, allowing them to match measured histories of temperature at various depths beneath a surface exposed to radiant heating.

The movement of liquid water is modeled by the continuity equation, the speed of liquid water motion being given by the product of the gradient of hydraulic potential and the hydraulic conductivity. A source term is included, being the local rate of condensation of water vapor. We believe that the "hydraulic potential" described here is rather the water (matric) potential expressed as equivalent water depth at standard gravity.

The movement of water vapor is modeled by a continuity equation, with local velocity of water vapor modeled as being equal to the product of the gradient of vapor pressure and "vapor conductivity" in analogy to hydraulic conductivity for the liquid phase. This parameter is proportional to the binary molecular diffusion coefficient and includes an empirical correction factor to be chosen by the model user.

The vapor pressure, e, is derived from the temperature-dependent saturation vapor pressure, e_s, scaled by a temperature sensitive exponential factor:

$$e/e_s = \exp(-\Phi M_w/RT)$$

where

Φ = "hydraulic potential" (must be converted to erg/gm)
M_w = molecular weight of water, gm/mol
R = universal gas constant, erg/mol K
T = absolute temperature, K

Note the conflict in dimensions of the parameters stemming from the fact that the unit of the "hydraulic potential" is given as length. If the acceleration of gravity is added as a factor in the numerator of the exponent, it becomes dimensionless. This is consistent with the formulation of Bhuiyan and others (1971), cited by Aston and Gill as the source for the liquid water motion model used. Bhuiyan and others use the same symbol, Φ, but identify it as the sum of the "pressure potential" and the "gravitational potential," the latter having the units of acceleration times length.

The authors did not use the vapor pressure formalism in the numerical examples they presented. Instead, e/e_s was assumed to be independent of temperature and was taken from an empirical equation relating it to volumetric water content for a particular soil. Again a source term was included in the liquid water continuity equation, being the negative of the water vapor source term.

Boundary conditions used for the computer implementation of this model are in the form of a specified surface temperature history. The moisture boundary condition is unspecified at the heated surface, but temperature and moisture content are held constant at a "deep" boundary, where their gradients vanish. Numerical results generated from the

computer code of Aston and Gill (1976) showed agreement with soil temperatures measured under a spreading grass fire (Scotter 1970). The temperature predictions of the model range from room temperature to over 400 °C, moisture contents treated range from bone dry to near saturation, and simulated time extended well beyond 200 minutes. These results are impressive considering that the model equations are mathematically "stiff" (Press and others 1986), and especially in light of the questionable features noted in the model for heat transport. Although this model's predictions agreed well with the data of Scotter (1970), the model has not performed well when applied under other conditions, and it appears to lack generality.

A Model Ignoring Moisture Movement—In using a model of heat transport in soil, one common prediction is whether certain plant components are killed by the thermal impact of a fire. Most plant tissue (excepting seed) is killed once its temperature is raised to 60 °C for a short time (Levitt 1980). How far below the surface of the mineral soil at a fire site is this maximum temperature achieved? The simplest model for predicting that maximal depth during a spreading fire is one that ignores moisture movement within the soil and treats the moist medium as an inert solid with constant constitutive parameters. Modeling the fire as a moving line heat source at the soil surface, Richon (1987) found that for the soil surrogate material properties explored, the problem could be simplified by idealizing the analysis to a one-dimensional transient situation. Steward and others (1990) extended this idealization to include cooling of the heated surface using a constant Newtonian film heat transfer coefficient. They found analytical solutions in dimensionless form for four different profiles of heat transfer rate as a function of time, with Newtonian cooling occurring either at all times or only after heating had ceased.

Soil can be treated as a medium with fixed properties and the fire treated as a transient boundary heating rate (to the extent that such approximations do not impose intolerable error), a treatment such as this is highly desirable. Using dimensionless variables, all situations of an entire class can be described by a single equation.

We cannot solely rely on models using moist soil as a medium with constant thermophysical properties. However, one must assume that, even though all the assumptions of the model are not valid, it may have adequate predictive power. Nevertheless extensive empirical justification is not yet available for this model.

Campbell's Model—Prominent soil scientist, Professor Gaylon Campbell of Washington State University, led a research team in developing a model for heat and moisture transport in soils applicable at the heating rates and temperature levels of soils under wildland fires. This model (Campbell and others 1992, 1995) embodies several significant extensions of deVries' formulation. It includes equations for predicting apparent soil thermal conductivity as a function of moisture content and temperature (Campbell and others 1994) and a new water content-humidity relationship for soils (Campbell and others 1993). It incorporates the advances in theoretical and empirical modeling of transport properties over the past 20 years (Campbell 1985).

Campbell and others (1992, 1995) model sensible heat accumulation as the difference between the divergence of the heat flux and the rate of heat absorption per unit volume by moisture evaporation. This is a fundamental difference from the approach taken by Aston and Gill. The heat flux is modeled as the product of apparent thermal conductivity and temperature gradient, and all soil components are assumed to have the same temperature at the same "point" in the continuum. Liquid water is treated as frozen in place, with its concentration changing because of evaporation. This simplification is justified on the grounds that liquid water movement is too slow to maintain equilibrium with the rapid temperature changes that are to be expected in the heating environment under a fire.

The flux density of water vapor is calculated as the negative of the product of vapor conductivity and the gradient of p, the partial pressure of water vapor, all multiplied by the "Stefan correction" $P/(P-p)$, where P is total atmospheric pressure. (This factor may or may not be appropriate over some range of water vapor partial pressure but is certainly not valid near the boiling point of water, where $p = P$ and the equation for vapor flux becomes singular. See appendix A for discussion of this factor). If we assume that the liquid water doesn't move, and neglect the rate of accumulation of water vapor, with respect to the other terms in the equation, the conservation of mass applied to water in the soil yields an equation linking the time rate of change of liquid water volume fraction to the divergence of the water vapor flux density. The liquid water fraction is in turn equated to a compact empirical function of the water (matric) potential that includes only two parameters: the water potential of ovendry soil and an empirical constant found to be approximately six times the air dry moisture fraction (Campbell and others 1993). This relationship alone is an important simplifying advance in the modeling process.

The apparent thermal conductivity model is an extension of deVries' (1963) model and is fully documented for the first time in Campbell and others (1994). It is complicated but straightforward, and incorporates latent heat transport by vapor flux.

The vapor conductivity model follows the formulation of Philip and deVries (1957), including the concatenation of empirical factors multiplying the binary diffusion coefficient of water vapor in air.

An important contribution in this model is its numerical integration scheme, which uses temperature and water potential as independent variables in expressions for the correction of the errors in the heat and mass conservation equations at each node. The integration scheme is fast and numerically stable over a wide range of test conditions.

This model represents an important advance and will be tested in field applications when it is available.

Other models—Three other models, taken from graduate theses, are firmly in the family of models from soil science, and the influence of the pioneering works is evident.

Schroeder (1974) developed an optimized computer simulation model for heat and moisture transfer in soils for a Ph.D. degree in computer science at Texas A&M University. In selecting a formulation to be implemented as the computer simulation, Schroeder summarized the equations describing moisture movement found in five publications. The only model that included heat transport was the model of Philip and deVries (1957) and deVries (1958). The deVries (1958) model is the one he chose to implement. Emphasis was on the efficiency of the computer code implementing the model, and not the model itself. There was no extension, development, or experimental verification of the model.

In contrast, the dissertation of Jury (1973), documents the writing and testing of a computer simulation, also discusses the physics underlying the processes modeled, and compares model predictions with experimental results. Cited as motivation for investigating the workings of the deVries' model (which is essentially the model he used) was in disagreement between experiment and theory (Jury 1973, p. 4):

> ...Several experiments have cast serious doubt on the present theoretical models of the coefficients used for describing the thermal transport of water in the liquid phase. None of the models has yet been able to predict detailed behavior in the vapor phase.

Jury presented a flowchart and FORTRAN listing of the program developed, but this particular model was not implemented for testing because it was not directed toward the temperature and heating regime associated with a fire environment. Nonetheless, Jury's thesis remains valuable for the physical concepts behind the mathematical expressions in these complicated models.

Peter (1992) directly attacked one of the situations that motivate the entire realm of study here: heat transfer in soil beneath a spreading fire. Peter documents four major areas of study:

1. Heat transfer within fires in a fuel bed
2. Heat transfer within dry mineral soil
3. Heat and mass transfer within moist soil
4. Heat and mass transfer within an organic layer undergoing smoldering combustion above mineral soil

Peter's work also includes coding of a computer simulation. The basis for the model is the formulation of deVries (1958), despite the reservations noted and the observations of deficiencies made by Jury (1973). The work leaves little room for conjecture. A working personal computer version of the simulation code could not be obtained for testing for this study. The numerical integration algorithm it contains was a supercomputer-based utility routine that is being replaced.

Luikov's Formulation—No survey of this field would be complete without acknowledging the broad contributions of the Russian scientist, A. V. Luikov, head of the Heat and Mass Transfer Institute of the Belorus Academy of Sciences. His major works are summarized in a survey paper (Luikov 1975), published posthumously.

Luikov's survey covers research contributions from the former Soviet Union to the field of heat and mass transport in porous media, by providing a mathematical synopsis of models developed at the Heat and Mass Transfer Institute. While it should have worldwide research community backing, little of the background work is accessible in English and the survey is not sufficiently detailed to permit replication of the computations exhibited. Our unsatisfying and inescapable conclusion is that the supporting work must be duplicated, but that Luikov's summary guidance should be valuable in that process.

Models from Engineering and Geophysics

Engineering and geophysics literature (see citations in Introduction) shows contrast between approaches to the formulation of models for heat and mass transport in porous media. Engineering approaches to modeling include Kansa and others (1977) who employed a model for heat and mass transport within a moist wood element undergoing pyrolysis to infer the theoretical influence of fuel moisture on the rate of pyrolysis. Moallemi and

others (1993) modeled the effect of water content on the smoldering combustion of woody materials. Kallel and others (1993) described drying bricks and curing concrete, as had Eckert and Faghri (1980). Cheng (1978) and Garg and Kassoy (1981) looked at geothermal energy in their model development. Rust and Roberts (1990) examined the role of buoyancy-induced convective heat transfer in saturated soil heated from above, through a building's concrete slab floor.

All these authors start with continuum transport equations for the conservation of mass for each phase, for the conservation of momentum, and for the conservation of energy. The unique character of the porous medium is incorporated through the constitutive relationships that define the continuum. Approximations are expressed in terms of influences on the constitutive relationships.

Kaviany (1991) and Cheng (1978) are especially instructive in terms of the differences between approaches. Because the conservation laws expressed as continuum transport equations deal with the concentrations—quantities per unit volume—of conserved extensive properties of material occupying the space in question, it is important to be precise in identifying the differential volume intended when "per unit volume" is used. For example, the term "mass of water vapor per unit volume" could refer to the local density of the water vapor in the gaseous phase, to the local average mass of water vapor per unit interstitial volume (some of which could contain liquid water), or to the local average mass of water vapor per unit volume of the soil medium (including interstices and whatever resides in them). These obviously are not equivalent quantities.

Cheng introduced three mathematical theorems that relate rates of change in space and time of the averages of properties taken over a small—nominally differential—volume of space, to averages over the same volume of the rates of change of the properties. Two theorems, one attributed to S. Whitaker and one to W. G. Gray, appeared in the literature of chemical engineering research. These fundamental relationships are applied to well-known transport equations applicable on the microscopic scale to each phase (solid, liquid, and gas) present in the porous medium. These relationships are manipulated to derive macroscopic volume-average equations applicable to the medium as a continuum, in which appear the properties of the phases used to describe them on the microscopic scale. Cheng noted that the conservation equations derived in this manner can also be obtained by careful consideration of a differential volume of the porous medium. Use of the averaging theorems keeps one aware of the ease with which flawed reasoning can arise.

Some papers focus on the numerical aspects of modeling the processes involved in heat and mass transport in porous media. Some investigations are substantive and even profound (Vafai and Tien 1989). Sometimes they are only mathematical exercises even though they bear titles that imply the physical processes modeled are themselves the subjects of investigation. For example, Thomas and others (1980) offer "a fully nonlinear analysis of heat and mass transfer problems in porous bodies" that is a highly simplified application of a formulation attributed to Luikov (1966) to analyze the process of kiln-drying lumber. The conclusion from this paper is that a linear theory with fixed constitutive parameters is adequate for this application. Similarly, Yeh and Luxmoore (1983) address "modeling moisture and thermal transport in unsaturated porous media" in an investigation related to the transport and dispersal of waterborne hazardous waste. The paper compares solutions of a contrived example by two different numerical methods, one of which is called "exact," the other identified only by an acronym.

The effects of experimental apparatus on the outcome of experiments also preoccupies some authors. If the concerns are valid, some of the cautions raised should be of interest to soil scientists even if the range of parameters is different. For instance, in laboratory experiments involving the heating of laterally confined moist soil samples from above or below, the region near the lateral boundary may offer much less resistance to the motion of fluid than does the bulk medium (Georgiadis and Catton 1988). This effect can arise if the lateral boundary is rigid, smooth, and impenetrable by the soil particles. This constraint can result in a looser packing of soil particles over a region of several soil particle diameters in extent near the boundary, forming a natural channel for "replacement air" to enter the medium if buoyancy causes the heated gas phase to exit vertically from the interior region.

Differences in Approach

In the engineering and geophysics literature, the movement of fluids through porous media is almost always modeled by the momentum equation in which diffusive mass transport is neglected. This equation expresses the acceleration of fluid in response to the forces acting upon it, where acceleration is set to zero and fluid velocity is such that the forces acting on the fluid are in balance. One such balance for liquid water in saturated soil equates the water pressure gradient to the drag resistance force per unit volume, which leads to Darcy's law in the limiting form as velocity approaches zero. In this limit, the drag force due to fluid flow over a small particle is

proportional to the velocity of the fluid rather than to the square of the velocity. In civil engineering literature, Darcy's law is extended to higher fluid velocities by multiplying the hydraulic conductivity by a factor involving the square of the fluid velocity, and known as the Forchheimer correction. Many other correction factors, modifications, and extensions of Darcy's law all stem from analysis of the momentum balance for fluids flowing through porous media. In the soil science literature, Darcy's law is properly identified as empirical, but no connection to fluid momentum conservation is made.

In the soil science formulation of Darcy's law, pressure is replaced by the "matric potential" that is essentially the Gibbs Free Energy (Philip 1975). This may be a convenient way to introduce the force associated with attraction between soil particles and liquid water such as are involved in capillary attraction and surface film formation. But by doing so, temperature and liquid water content sensitivities of a highly nonlinear character and of uncertain dependence on the nature of the soil medium are introduced where only the well-known temperature dependence of the viscosity of water existed before. If the force associated with attraction between liquid water and soil matrix had been represented by a separate term in the momentum equation, it would be conceptually clear, though the final result could mathematically be the same. A threshold effect, in which the attraction between water and quartz solid vanishes abruptly near 65 °C (Churaev 1975), would be easier to quantify if separated from the masking effect of diminishing water viscosity with increasing temperature.

Another term appearing in the momentum equation is the body force due to buoyancy, which arises from the difference between the local static pressure gradient and the local fluid density. If the porous medium is open laterally to the ambient pressure field, then its gradient establishes the static background within which a density defect results in a net force per unit volume equal to the microscale average density defect times the acceleration of gravity. Even if the local soil environment is physically isolated from the ambient pressure field, a buoyancy force can yet arise from a nonuniform temperature field, if the density of the fluid changes with temperature. The effect of buoyancy is important in geothermal processes and is often manifested in Benard convection cells that transport large volumes of liquid water (Cheng 1978; Garg and Kassoy 1981) and therefore large quantities of sensible heat. But by inducing liquid phase convective flow, heat transfer can be significantly altered (Rust and Roberts 1990).

A buoyancy force should also be in evidence in the motion of water vapor in the heated soil under a fire. Unless a one-dimensional idealization of the process is carried to the extreme that air is excluded from the hot soil under the fire, so the atmosphere's ambient hydrostatic pressure field does not penetrate into the soil, a local density defect should give rise to a substantial vertical body force. This would cause the air and water vapor that make up the gas phase to rise. The rising motion would be resisted by inertia (including entrainment of stationary or slower moving fluid) and friction with the soil medium. The net movement of the gas phase components would include molecular diffusion of the constituents relative to the moving bulk medium.

If there is a net upward motion of the hot gas phase, there may be a replenishing inflow of ambient air that cannot be accommodated within the idealization of a one-dimensional model. The "replacement air" inflow might be idealized as confined laterally to seams, fissures, or other soil nonuniformities, with lateral dispersion at all depths as demanded by the continuity equation for the gas phase. Vertical variation of the lateral velocity field for this flow could be described by the momentum equation integrated over a lateral region bounded by edges along which air inflow occurs. Documenting this speculative discussion indicates that, while the one-dimensional idealization poses conceptual problems to the analyst, who would incorporate buoyancy into the gas phase momentum equation, the problems are not seen as insurmountable. By determining the lateral scale of convective cells (Koschmeider 1993) and reducing dimensionality using Galerkin averaging or some similar method, a self-consistent and simplified one-dimensional model should be achieved. This speculation applies only to models based on the engineering paradigm, as buoyancy terms are neglected in models in soil science. Vafai and Tien (1989) reported their numerical investigations showed that only at "high" pressure gradients can a one-dimensional approximation be used for combined heat and mass transport in porous media.

Often soil science models, like engineering models, include the effect of gravity on the liquid water phase. The phase composition of the interstitial fluid, in the region where liquid water exists, can vary from all gas to all liquid, making the modeling of this region one of the most intricate and challenging. It should be possible to represent the interstitial fluid as a single continuum consisting of two intermingled phases whose relative abundance varies spatially and temporally (Vafai and Tien 1989). Instead, separate models for the gas and liquid phases are developed and combined with the dismissal of relatively small terms. A comprehensive model of the two-phase regime may reside in the petroleum engineering literature.

The movement of water vapor in soil is modeled as molecular diffusion in all the formulations from the soil science literature. Molecular diffusion is a process of mixing in which the velocity of one species of molecule relative to another through which it is moving is proportional to the gradient of the molecular concentration of the diffusing species. These models are almost always formulated in terms of the gradient of water vapor pressure or relative humidity and usually include a nonlinear enhancement factor—the Stefan correction—that may not be appropriate (see appendix A). The vapor pressure is in turn related to the local temperature so the concentration gradient is determined by the local temperature gradient, and the process of heat transfer by vapor transport is seen phenomenologically to mimic thermal conduction. The complexity of this connection prevents its explicit modeling, but the analysis serves as a guide to definition and interpretation of the appropriate empiricism.

Expressing the conservation of energy by equating the accumulation of heat per unit volume to the negative of the divergence of the rate of transport of heat via mass motion and bulk medium thermal conductivity closes the equation set. It also strongly couples the models for heat and mass transport. As the water vapor diffusion model is a strong function of temperature, movement of water vapor in response to temperature gradients theoretically results in strong temperature dependence of the apparent thermal conductivity of the air that fills the interstices between soil particles not filled with liquid water. Because the latent heat of vaporization of water multiplied by the mass flux of water vapor represents the transport of energy, while, as noted, diffusion of water vapor is modeled in part as nonlinearly proportional to temperature gradient.

Because of the uncertainty and complexity of the dependence of heat transport upon water vapor movement, any model must rely to some degree upon an empirically determined apparent thermal conductivity that depends on temperature, water content, and soil characteristics. This procedure might predict transient temperature fields with high fidelity, yet fail to describe transient moisture distributions accurately. The heat transfer boundary conditions determine the temperature field from which the moisture transport can be inferred. Though oversimplified, the characterization that the soil science models derive the moisture distribution from the temperature field is not strongly at variance with the literature reviewed.

Engineering and soil science differences are evident in the treatment of heat transfer. The formulation based on continuum mechanics distinguishes between energy transported by mass motion and heat transferred through the constituents of the medium. Temperature fields for each of the components (solid particles, liquid water, interstitial gas composed of air and water vapor) would be determined from the heat transferred to and from each phase and the transport of heat by its mass motion. The temperature of each of the components need not necessarily be the same everywhere. Temperature differences could result in significant heat transfer by vapor transport through and condensation on cooler soil particles relatively far from the point at which the water evaporated. Likewise, superheating of vapor rising through hot, dry overburdened soil could reduce heat flux to the moist soil below.

A model constructed from a more general perspective could offer some advantages. It should collapse, in the proper limits, to a diffusion driven (soil science type) model or to an engineering model (with diffusive terms neglected) covering the same phenomenology. It should contain within it the competing terms that are dismissed, allowing quantitative definition of the ranges of validity of the specialized limiting forms.

Computer Programs Exercised

The Montana State University contingent converted two models to FORTRAN suitable for application on personal computers to facilitate testing of the models for their accuracy in predicting results of experiments at the Intermountain Fire Sciences Laboratory. We present results from testing two models, Aston and Gill (1976) and Campbell and others (1992).

The model of Aston and Gill (1976) as supplied by the Fire Lab to the University study team was transcribed to a dialect of FORTRAN acceptable to Microsoft FORTRAN 5.0. The model was exercised to create temperature and soil moisture field histories (examples of the output in figs. 1 and 2). The aberrant behavior of the temperature histories at the shallower depths is not unique to the new version of the model. The same behavior had been noted by Fire Lab researchers in exercising a version of this model adapted to the Data General at the lab.

Further testing, relying on soil constitutive parameter tables generated using Campbell's (1985) predictive models, confirmed that the numerical integration scheme used in the Aston-Gill model becomes unstable when a simulated soil layer becomes nearly dry (Albini and Amin 1994). The equations are remarkably "stiff," a characteristic that often forces use of special numerical techniques (Press and others 1986). This feature was noted by the model

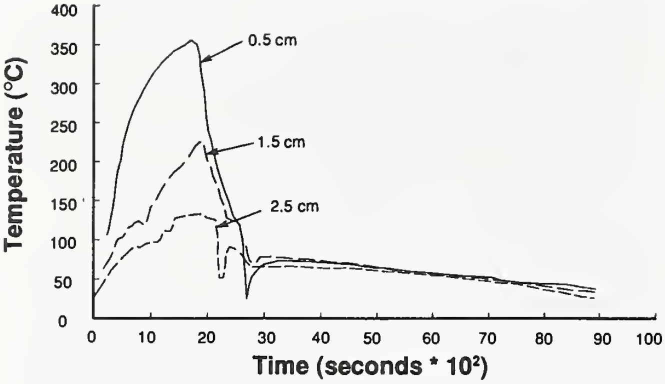

Figure 1—Temperature histories at various depths predicted by Aston-Gill model. Depth 1 is 0.5 cm below the surface, depth 2 at 1.5 cm, and depth 3 at 2.5 cm. The surface temperature is a rising exponential followed by a decaying exponential in time, much like the temperature history at depth 1. Note the aberrant behavior between 2,000 and 3,000 s.

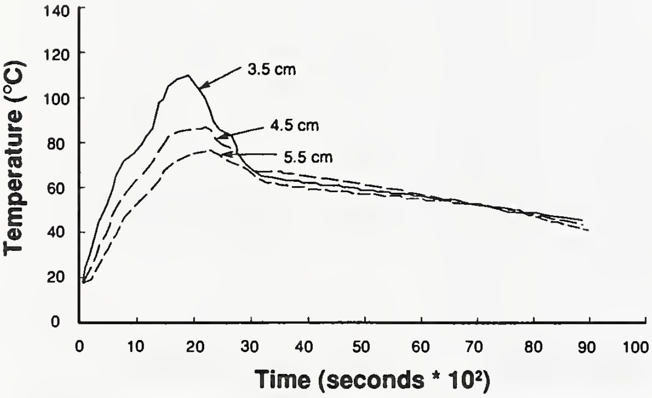

Figure 2—Temperature histories at greater depths, as predicted by the Aston-Gill model for the conditions of figure 1. Depth 4 is 3.5 cm beneath the surface, depth 5 at 4.5 cm, and depth 6 at 5.5 cm. These histories do not misbehave as badly as do those shown in figure 1.

builders, but they used a second order Runge-Kutta integration scheme that is not robust against the severely nonlinear dependencies arising in many cases of soil heating by fire.

The model of Campbell and others (1992) was provided to the University study team in Turbo Pascal source code. It was translated into Microsoft FORTRAN 5.0, compiled, and exercised (example output in figs. 3 to 6). These results simulate experiments in which the upper surface of a soil sample was exposed to a powerful radiant heater. The upper surface temperature histories were brought into agreement by adjusting the parameters that describe the upper surface heat input rate. With these parameters fixed, predictions of thermal and moisture response were made for a wide variety of soils under various initial moisture conditions. Measurements of the temperature at various depths showed good agreement with the model's predictions (Campbell and others 1992, 1995).

Campbell and others (1992, 1995) compare numerous experimental and theoretical results; in almost every case, the model predicts at least the high temperature field history with good accuracy, but yields relatively large errors in prediction of moisture content histories. A later variant of this model (Campbell and others 1995) should improve the accuracy of moisture content predictions. The measurement of local moisture concentration in soils, even in the laboratory, is difficult without disturbing the experimental conditions. The temporal and spatial resolutions of nonintrusive instruments are inadequate, and high resolution methods are intrusive.

The Aston and Gill (1976) model is not in a usable state at this time. The Campbell and others (1992) model is now available in two source languages, is operable on personal computers, and is fast and easy to use in either variant. It seems to perform well in describing the transient temperature fields found in laboratory experiments. Although its prediction of moisture movement is not well validated by laboratory measurements, it may satisfy all requirements for a general heat transfer model for fire effects prediction. It clearly should be tested for this purpose.

Opportunities for Model Improvement

Opportunities for possible improvement in the modeling of heat and mass transport in soils heated

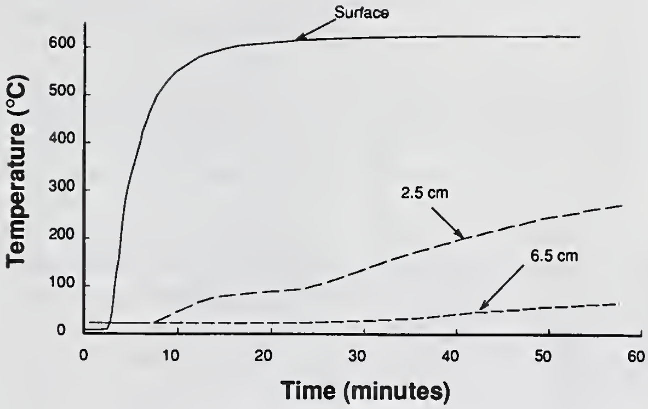

Figure 3—Temperature histories predicted by the Campbell model for soil surface and two depths beneath the surface. Radiant heating by a high powered lamp in a laboratory experiment is simulated. The soil is air dry Boulder Creek silt loam at an initial moisture content of 6 percent.

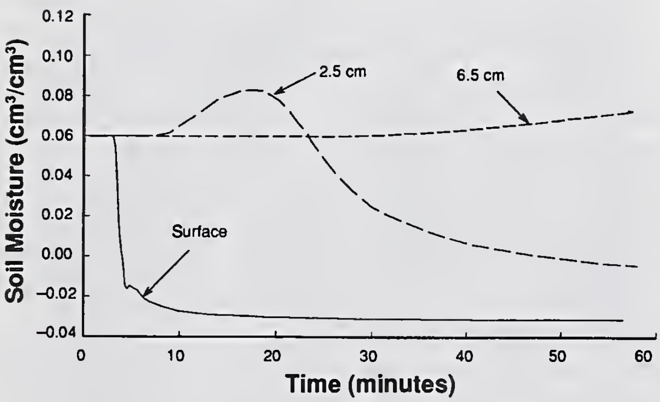

Figure 4—Moisture content histories corresponding to the temperature histories displayed in figure 3, as predicted by Campbell's model. Temporary rise in moisture content at 25 mm depth indicates an initial vapor migration downward. Zero moisture content refers to 105 °C ovendry condition, so negative moisture predictions are physically meaningful.

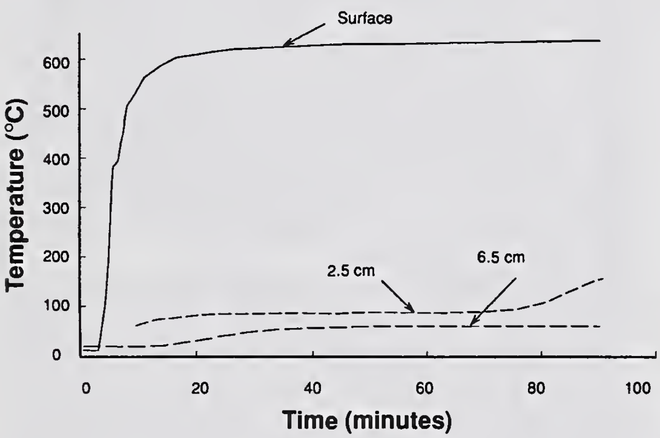

Figure 5—Temperature histories predicted by Campbell's model for the same soil and heating conditions of figure 3, but with initial soil moisture of 22 percent. Note the higher temperatures at 65 mm depth, presumably due to higher thermal conductivity in the wetter soil.

by fires must be viewed as hypothetical. They are offered here as suggestions for the creators of the next generation of models. They fall into two categories:

1. Identification of phenomena left out of models that might prove to be important.
2. Identification of complicating features included that might prove to be unnecessary.

Possible Important Omissions

Models developed for engineering applications almost always ignore diffusive transport of water as vapor or as liquid, and so lack representation of this phenomenology. Such models can only be accurate in the limiting situation that diffusive mass motions can be neglected. Since the applicability of the limit

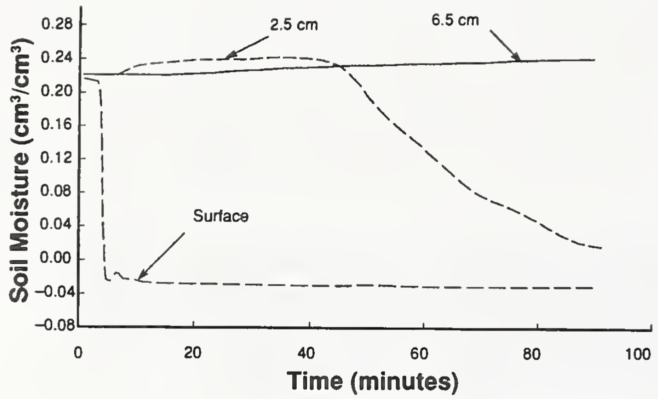

Figure 6—Moisture histories corresponding to the temperature histories shown in figure 5. Transient increase in moisture content is predicted for 25 mm depth. Zero moisture content refers to 105 °C ovendry condition, so negative moisture predictions are physically meaningful.

cannot be inferred from the content of the models, they are fundamentally deficient for this application. Therefore, we address omissions in the formulations of models with soil science ancestry.

Omission of the momentum equation from the primitive set appears to be unjustified. Clearly, if heat is supplied rapidly to very moist soil, the soil medium eventually will emit steam at a rate that cannot be carried away by the process of vapor diffusion. A pressure gradient would develop, negative upward, that would assist the (omitted) buoyancy force in expelling the steam in a massflow process. This flow would inhibit the transfer of heat, and a pseudosteady state is conceivably achievable.

The problem of predicting the transient movement of the phase-change boundary (the classical "Stefan problem") is modified by the heat transported by the vapor phase massflow counter to the flow of heat from fire to moist soil. It could even require an eigenvalue solution. This would be a most interesting theoretical development and could have quite important fire effects implications in the field.

The assumption that all components of the soil medium have the same temperature at each point has strong heuristic appeal. The assumption may have arisen from the piecemeal assembly of an energy transport equation starting with Fourier heat conduction and an apparent thermal conductivity for the medium. The variations in this equation among model authors arises from the primitive equation set chosen, which is not a fundamental one. A continuum mechanics approach, with multiple fluid components occupying the interstices of a solid matrix, would readily allow separate temperature distributions for each of the components. The heat transfer rates between components would have to be modeled. Such a model should predict the conditions under which the assumption is valid that all components locally have the same temperature.

We did not discover a treatment of lateral nonhomogeneity from soil science sources, nor did we find an example of a systematic reduction of dimensionality by starting with a three-dimensional model and applying averaging to reduce the model to one dimension. This is true despite watershed works of Philip and deVries (1957) and of deVries (1958) that formulated the process descriptions in three-dimensional form. This could contribute to the difficulties in predicting moisture movement that have beset these models (Campbell and others 1992; Jury 1974). This implication arises because a one-dimensional model imposes the decision as to the direction of vapor movement to be based on possibly competing responses to thermal and moisture gradients. This allows the possibility of a zero-velocity front that marks a boundary between vapor moving in the direction of heat flow (aiding heat transfer) and moving in the direction counter to heat flow. We have not discovered a thorough discussion of this phenomenology. A model that countenances lateral movement of water vapor and interstitial air might alleviate such complications.

Finally, we have seen no accommodation or repudiation of the effect documented by Churaev (1975) that the wetting attraction of liquid water to the interior surfaces of quartz capillary tubes rapidly goes to zero with increasing temperature near 65 °C. If this phenomenon occurs, does it occur in sandy soils also? If not, why not? If it occurs, there should be a different dependence of water matric potential on moisture content at high temperature than at low. This potentially important phenomenon appears to have been ignored. Either that, or we have failed to unearth the definitive dismissal of the importance of this phenomenon to moisture movement in heated soils. This phenomenon needs to be investigated further.

Possible Simplifications

Models from soil science ancestry are complex and could be simplified without seriously degrading their capabilities to predict heat and mass transport in soils heated by fires. The modifications necessary to render engineering models applicable to fire-driven heat and mass transport in soils amount to the addition of contributions to mass transport.

The apparent thermal conductivity used to model heat transport in soils employed by deVries (1958) is more clearly rationalized by Campbell and others (1994). In the earlier formulation, latent heat transport by vapor movement is modeled by invoking the condition that vapor movement is controlled by temperature dependence of the rate of diffusion of water vapor. Using this formulation makes the apparent thermal conductivity a strongly nonlinear function of moisture content and of temperature and requires the use of a source or sink term in the Fourier equation employing the apparent conductivity. The predicted contribution of vapor movement to apparent thermal conductivity seems to require an empirical adjustment that increases it by an order of magnitude. Under the high heating rates and temperatures of fire-driven heat transfer, it is conceivable that a formulation based on a more primitive equation set would be simpler. The movement and temperature of each of the phases in the bulk medium would be modeled separately, taking into account heat transferred between phases. Limiting case approximations might be more transparent under such a formulation.

The descriptions of vapor movement used in the models based on soil science rest upon Fick's law for binary molecular diffusion. This law states that the net flux of molecules (number of molecules per unit area per unit time) is proportional to the negative gradient of the concentration of such molecules. Applied to the interstitial gas phase treated as a binary mixture or air and water vapor, yields a macroscopic phenomenological equation that has two multiplicative empirical factors: the "tortuosity" correction, usually taken to be about two-thirds, and an "enhancement" factor that ranges between 5 and 10. In addition, the "Stefan correction" (see appendix A) is applied, which increases the calculated flux of water vapor molecules by a factor proportional to the ratio of the ambient pressure to the partial pressure of air. When the local temperature approaches the boiling point of water, this factor becomes infinite if there is any liquid water present, so it must be limited to some maximum value, usually less than 10.

In the engineering literature, water vapor movement in porous media is treated as part of the gas phase. The temperature of and the local heat transfer rate to the liquid water component and the local concentration of water vapor in the gas phase are modeled as influencing the local rate of evaporation. The gas phase moves through the interstitial pores of the soil matrix that are not blocked by liquid water at a rate fixed by the local pressure gradient, gas friction with the stationary matrix, and body forces acting on it. This model results in a high-gas phase velocity on the microscopic scale, relative to the mass motion velocity on the macroscopic scale. Temperature sensitivity of the viscosity of the gas phase and coupling of the heat transfer and mass motion equations render this model fully as nonlinear and as complicated as the soil science model, if it is reduced by combining equations to derive an equivalent to the "vapor conductivity" used in soil science models. Because each step in the process can be described separately, the model is conceptually simpler and its failure points more readily identifiable when comparing experimental data to predictions. The diffusion of water vapor in this model would only serve to disperse the water vapor through the gas phase and would not be modeled explicitly but would be assumed to have resulted in local lateral uniformity. Contributions to mass motion from diffusive water vapor movement are neglected in these formulations, so the Stefan correction would play no role. Neglect of vapor diffusion would mean that the model should not collapse to one derived from soil science in the limit of small thermal gradients and heat transfer levels.

Some soil science models account for the movement of liquid water and the transport of sensible heat thereby (Aston and Gill 1976; Peter 1992), while Campbell and others (1992, 1995) model liquid water as being "frozen in place" in fire-heated soils. This simplification seems justified given that the flux of liquid water in soil is governed by the product of hydraulic conductivity and gradient of water potential. The highly nonlinear behavior of the hydraulic conductivity with soil moisture content introduces mathematical sensitivity near the dry condition that may require special attention in modeling. Yet the movement of liquid water, even at extreme temperature and moisture gradients, is slow relative to the movement of heat (as measured by the rate of advance of an isotherm at less than the boiling point), and its motion transports little heat. Retention of this assumption would be helpful in assembling a heat and mass transport model from the continuum mechanics approach. Overlooking some important phenomenology associated with a temperature threshold for the surface wetting attraction between liquid water and soil minerals (Churaev 1975) would justify retaining a model for liquid water movement in the circumstances that the model is intended to be used.

Conclusions

Our literature survey and study of models for heat and mass transport in soils exposed to heating rate and temperature regimes expected under wildland fires has led us to conclude:

- The soil science field has contributed the only useful models for phenomenology readily available to investigators of wildland fire effects.
- The model of Campbell and others (1992, 1995) seems to perform well in predicting temperature histories, at various depths, of soils heated on their upper surfaces at rates, and to temperatures expected under wildland fires. It does not seem to predict soil moisture content histories nearly as well as it does temperature histories, at least in the early variant examined here.
- An alternative model can be described as a continuum mechanics approach usually used within the engineering disciplines. This uses a more fundamental set of primitive equations and could more readily allow for nonequilibrium interactions between the constituents of the soil medium. Such a model should be modified to include diffusive mass motion of water vapor and liquid water as well.
- We have identified the omission, in soil science models, of several important features. Conversely, some complicating aspects of such models might contribute only negligibly to heat or mass transport. Their dismissal might simplify the modeling with little sacrifice in fidelity.

Acknowledgments

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Appendix A: The Stefan Correction for Confined One-Dimensional Diffusion

Consider the steady state diffusion of water vapor through air under the following constraints and assumptions:

1. The flow takes place in a small diameter horizontal tube, so motion is confined to one direction and gravity plays no role.
2. The left end of the tube, at $x = 0$, is immersed in liquid water so there can be no movement of air through that boundary.
3. The right side of the tube is open to the ambient atmosphere, so the fluid in the tube supports no pressure gradient along its length under steady state conditions.
4. Ambient relative humidity is less than 100 percent, so water evaporates from the liquid phase surface and escapes into the atmosphere.
5. Both air and water vapor can be idealized as perfect gases, and the processes within the tube take place at ambient temperature.

If water vapor is to diffuse along the length of the tube, moving from left to right, then there is a gradient in the concentration of water molecules, increasing from right to left. There must also be a countervailing gradient in the concentration of air molecules, so air diffuses from right to left. Since air cannot escape the tube at its left end, unlike the water vapor that escapes at its right end, there must be a general flow of the air-water vapor mixture from left to right, keeping the net movement of air at zero. This general flow acts to increase the transport speed of the water vapor, increasing the "effective diffusion coefficient" of the water vapor through air. Stefan (1874) first documented this phenomenon. The following derivation follows Jakob (1956).

Nomenclature:

- C concentration, mol/volume
- D bimolecular diffusion coefficient, length^2/time
- M molecular weight, mass/mol
- m″ mass flux, mass/area x time
- P (partial) pressure, energy/volume
- R perfect gas constant, energy/mol x degree
- T (absolute) ambient temperature
- U convection velocity, positive left to right, length/time
- x distance along tube, positive left to right

Subscripts

- 0 total (ambient)
- 1 refers to air
- 2 refers to water vapor

1.	$P_1 + P_2 = P_0$	Constant pressure
2.	$C_1 = P_1/R\,T_0$	Air is perfect gas
3.	$C_2 = P_2/R\,T_0$	Water vapor is perfect gas
4.	$m_1'' = M_1(C_1U - D\,dC_1/dx) = 0$	No net air flux
5.	$m_2'' = M_2(C_2U - D\,dC_2/dx)$	Net water vapor flux
6.	$P_1\,U = D\,dP_1/dx$	4. and 2.
7.	$P_2\,U = D\,dP_2/dx + R\,T_0\,m_2''/M_2$	5. and 3.
8.	$P_0\,U = R\,T_0\,m_2''/M_2$	6. + 7. and 1.

Solve 8. for U, to be used in 5. Solve resultant for m_2'' to find:

$$m_2'' = -\,[P_0/(P_0 - P_2)]\,M_2\,D\,dC_2/dx.$$

The factor in square brackets is the "Stefan correction" that increases the effective value of the diffusion coefficient D. The equation breaks down as the value of P_2 approaches P_0. The flaw in reasoning is that the assumed steady state will not be achieved.

Albini, Frank; Amin, M. Ruhul; Hungerford, Roger D.; Frandsen, William H.; Ryan, Kevin C. 1996. Models for fire-driven heat and moisture transport in soils. Gen. Tech. Rep. INT-GTR-335. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

A survey was conducted of predictive models for heat and mass transport within soils exposed to the heating rates and temperature regimes under wildland fires. Two models trace their ancestry to soil science, and other models for heat and mass transport in porous media come from engineering disciplines and geophysics. The approaches underlying the development of the models were contrasted. Opportunities for improving the robustness and fidelity of currently available models were sought and a few potentially important omissions were identified, along with some complicating features that might be ignored without significant loss of realism.

Keywords: fire effects, heat transfer, heat transport, mass transport, soils, modeling

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

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